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# Sudden survival improvement in critical neurotrauma: An exploratory analysis using a stratified statistical process control technique

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ABSTRACT

*Background:* Outcome after trauma depends on patient characteristics, quality of care, and random events. The TRISS model predicts probability of survival (Ps) adjusted for Injury Severity Score (ISS), Revised Trauma Score (RTS), mechanism of injury, and age. Quality of care is often evaluated by calculating the number of "excess" survivors, year by year. In contrast, the Variable Life-Adjusted Display (VLAD) technique allows rapid detection of altered survival. VLAD adjusts each death or survival by the patient's risk status and graphically displays accumulated number of unexpected survivors over time. We evaluated outcome changes and their time relation to trauma service improvements.

*Methods:* Observational, retrospective study of the total 2001–2011 trauma population from a Level I trauma centre. Outcome was 30-day survival. Ps was calculated with the TRISS model, 2005 coefficients. VLAD graphs were created for the entire population and for subpopulations stratified by ISS level, ISS body region (Head/Neck, Face, Chest, Abdomen/Pelvic contents, Extremities/Pelvic girdle, External), and maximum Abbreviated Injury Scale (maxAIS) score in each region. Piecewise linear regression identified VLAD graph breakpoints.

*Results:* 12,191 consecutive trauma patients (median age 35 years, 72% males, 91% blunt injury, 41% ISS $\geq$ 16) formed the dataset. Their VLAD graph indicated performance equal to TRISS predicted survival until a sudden improvement in late 2004. From then survival remained improved but unchanged through 2011. Total number of excess survivors was 141. Inspection of subgroup VLAD graphs showed that the increased survival mainly occurred in patients having at least one Head/Neck AIS 5 injury. The effect was present in both isolated and multitraumatised maxAIS 5 Head/Neck trauma. The remaining trauma population showed unchanged survival, superior to TRISS predicted, throughout the study period.

Important general and neurotrauma-targeted improvements in our trauma service could underlie our findings: A formalised trauma service, damage control resuscitation protocols, structured training, increased helicopter transfer capacity, consultant-based neurosurgical assessment, a doubling of emergency neurosurgical procedures, and improved neurointensive care.

*Conclusions:* Stratified VLAD enables continuous, high-resolution system analysis. We encourage trauma centres to explore their data and to monitor future system changes.

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## Introduction

Outcome after trauma is a function of patient characteristics, quality of care, and random events [1]. For hospital benchmarking it is necessary to adjust for the risk profile of the patients to remove sources of variation that are independent of quality of care. Without risk stratification, trauma centres treating the most severely injured patients will appear to have worse results than others. This may influence on referral patterns and resource allocation and even discourage the treatment of high-risk patients.

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Such consequences are particularly undesirable as high-risk patients probably gain most from referral to the highest level of care.

Several risk stratification models in trauma exist, incorporating e.g. anatomical injury, physiological derangement, mechanism of injury, age, gender, and pre-injury comorbidity to predict probability of survival. By applying such a model to all patients in a cohort, the actual number of survivors can be compared to the predicted number of survivors calculated as the sum of all survival probabilities. Thus, a trauma centre will be able to find and follow discrepancies between its own performance and a standard, even if its referral patterns and injury profiles are different from other hospitals and change over time. A norm in this kind of benchmarking is the *W* statistic, defined as the difference between observed and predicted survival rates, i.e. the number of unexpected survivors, per 100 patients [2].

Trauma care performance is often evaluated year by year. This approach eliminates apparent performance fluctuations due to e.g. seasonal changes in injury patterns. However, year-by-year evaluation also prevents detection of short-lasting variations in performance that may be of particular interest. Examples are recurring performance deteriorations caused by vacations or rotation of personnel groups, and random performance drops caused by coincidental pile-ups of sick leaves or by hospital reorganisation.

Alternative approaches based on statistical process control techniques allow rapid detection of events that affect patient survival. One such technique is the Variable Life-Adjusted Display (VLAD), a refinement of the cumulative sum method. VLAD adjusts each death or survival by the patient's risk status and provides a graphical display of accumulated number of unexpected survivors over time, with a high time-resolution. The number of excess saved lives per 100 patients, read from the *y*-axis of the VLAD graph, is equal to the *W* statistic. VLAD charts are also known as cumulative risk-adjusted mortality charts.

The VLAD technique was developed in cardiac surgery and is much used to monitor intensive care unit (ICU) performance [3–5]. In the trauma literature, few publications using the VLAD technique exist. In a study of a seven-year trauma population (2002–2008) from the Oslo University Hospital Trauma Registry (TR–OUH) the VLAD technique demonstrated a sudden increase in survival among the most injured patients, starting from the beginning of 2005 [6,7]. The performance change coincided in time with an organisational change in the hospital trauma care. In the current study we utilised the VLAD technique to systematically explore a superset of that population (2001–2011), with the aim of finding the patient subgroups in which the survival changes occurred. Patients were stratified by the body regions and injury severity codes that represent the anatomical injuries in the underlying Trauma Score – Injury Severity Score (TRISS) model used for risk adjustment [8].

A number of qualitative and quantitative changes were implemented in our trauma service during the study period, e.g. in the pre-hospital services, in the systematic care of all trauma admissions, including a strengthened focus on neurotrauma patients, in the treatment of massive bleeding, and in structured training of trauma team members. We explore and discuss clinical and organisational changes that may underlie the increased survival observed in the identified patient subgroups.

## Methods

### *Population*

This was an observational, retrospective study of eleven years of anonymised trauma registry data from a single Norwegian Level I trauma centre. The study was approved and the need for written informed consent was waived by the institutional Privacy Ombudsman for Research, on behalf of the Norwegian Data Protection Authority and the Regional Committee for Medical Research Ethics. We aimed to adhere to the STROBE Guidelines (http://www.strobe-statement.org) in our reporting.

Oslo University Hospital, Ullevål (OUH–U) is a Level I trauma referral hospital currently covering a population of 2.8 million inhabitants. The study evaluated trauma care performance in all patients included in the Oslo University Hospital Trauma Registry (TR–OUH) in the period 2001 through 2011. Inclusion criteria for TR–OUH were (a) all trauma patients admitted through trauma team activation, irrespective of Injury Severity Score (ISS) [9], (b) patients with penetrating injuries proximal to the elbow or knee, (c) patients with head injury of Abbreviated Injury Scale [10] (AIS) severity code $\geq$3, and (d) patients with ISS $\geq$ 10 admitted to OUH–U directly or via a local hospital <24 h after injury. Patients transferred $\geq$24 h after injury and patients with an isolated fracture of a single extremity were included only if the trauma team was activated upon their arrival at OUH–U. All eligible patients transported to the OUH–U emergency room (ER) were included; patients classified as dead on arrival were not excluded.

### *Variables*

Outcome was survival 30 days after injury, determined by hospital records and information from the Norwegian Population Registry. Some foreign citizens were discharged alive to their home country less than 30 days after injury; these were coded as survivors. Predictive, system characteristic, and process mapping variables used (Table 1) were defined according to the revised Utstein template for uniform reporting of data following major trauma [11].

Probability of survival (Ps) was calculated according to the TRISS model using the National Trauma Data Bank (NTDB) 2005 coefficients [12]. *W* statistics for selected subgroups were calculated from the Ps values; standard error of the *W* statistic was defined as *W*/*Z* [2].

Variables used in the TRISS model were mechanism of injury (blunt or penetrating), patient age, Revised Trauma Score (RTS) [13], and ISS. The ISS was calculated from anatomical injury descriptors according to the Abbreviated Injury Scale 1990 Revision Update 98 (AIS 98) [10], by summing the square of the highest AIS severity scores for the three most seriously injured ISS body regions. New Injury Severity Score (NISS) was also calculated from AIS 98, by summing the square of the patient's three highest AIS severity scores independent of injured ISS body region [14].

RTS category scores (0–4) for Glasgow Coma Scale (GCS) score, systolic blood pressure, and respiratory rate upon arrival in the ER [11] were used to calculate the weighted RTS score in the TRISS model. For patients with missing physiological data from the ER (e.g. missing respiratory rate due to artificial ventilation), TR–OUH assigns the last documented physiological measurement before admission, either by the ground ambulance or Helicopter Emergency Medical System (HEMS) personnel or from the physician in the ER of the referring hospital. In cases where no actual values are documented, the trauma registrar assigns an RTS category score judging from clinical descriptions in patient records, if possible. A normal RTS category score (4) is assigned if no documentation exists, to avoid biasing outcome data in the hospital's favour.

Triage Revised Trauma Score (T-RTS) (0–12) was calculated for the pre-hospital scene, at any transferring hospital, and in the OUH–U ER by summing the relevant RTS clinical category scores (0–4) [13] for GCS, systolic blood pressure, and respiratory rate. Pre-injury comorbidity was classified according to the American

**Table 1**
Values of descriptive variables in patient subgroups.

| Variable | Period | No Head/Neck injury of AIS 5 | Present Head/Neck injury of AIS 5 | Isolated Head/Neck injury of AIS 5 | Multitraumatised Head/Neck injury of AIS 5 |
|---|---|---|---|---|---|
| Number of admitted patients in period (yearly average) | 1 | 3075 (769) | 363 (91) | 174 (44) | 189 (47) |
| | 2 | 7865 (1123) | 888 (127) | 453 (65) | 432 (62) |
| Age, years | 1 | 33 (15–68) | 45 (15–80) | 56 (15–83)$^{\#\#}$ | 34 (14–74) |
| | 2 | 34 (13–68) | 48 (18–79) | 56 (18–81)$^{\#\#}$ | 38 (17–71) |
| Male gender, *n* (%) | 1 | 2203 (72) | 260 (72) | 123 (71) | 137 (72) |
| | 2 | 5659 (72) | 655 (74) | 331 (73) | 324 (75) |
| Pre-injury ASA-PS ≥3, *n* (%) | 1 | 215 (7.0) | 73 (20) | 48 (28)$^{\#\#}$ | 25 (14) |
| | 2 | 753 (9.6)$^{**}$ | 221 (25) | 173 (38)$^{\#\#}$ | 48 (11) |
| Dominant injury Blunt, *n* (%) | 1 | 2773 (90) | 343 (94) | 159 (91)$^{\#}$ | 184 (97) |
| | 2 | 7091 (90) | 844 (95) | 433 (95) | 411 (95) |
| Fall, *n* (%) | 1 | 734 (24) | 158 (44) | 108 (62)$^{\#\#}$ | 50 (27) |
| | 2 | 2154 (27)$^{**}$ | 439 (49) | 308 (68)$^{\#\#}$ | 131 (30) |
| Transport injury, *n* (%) | 1 | 1668 (54) | 152 (42) | 32 (18)$^{\#\#}$ | 120 (63) |
| | 2 | 3607 (46)$^{**}$ | 291 (33)$^{**}$ | 54 (12)$^{\#\#}$ | 237 (55) |
| Violence, *n* (%) | 1 | 314 (10) | 10 (2.7) | 9 (5.2)$^{\#\#}$ | 1 (0.5) |
| | 2 | 931 (12)$^{*}$ | 61 (6.9)$^{**}$ | 34 (7.5)$^{\#\#}$ | 27 (6.2) |
| Pre-hospital GCS sum | 1 | 15 (7–15) | 4 (3–14) | 5 (3–15)$^{\#}$ | 3 (3–9) |
| | 2 | 15 (8–15)$^{*}$ | 6 (3–15)$^{**}$ | 8 (3–15)$^{\#\#}$ | 5 (3–15) |
| Pre-hospital T-RTS sum | 1 | 12 (10–12) | 8 (4–12) | 10 (6–12)$^{\#\#}$ | 8 (2–10) |
| | 2 | 12 (10–12) | 9 (6–12)$^{**}$ | 11 (7–12)$^{\#\#}$ | 9 (5–12) |
| Physician-manned primary transport (ground or air), *n* (%) | 1 | 732 (24) | 121 (33) | 34 (20)$^{\#\#}$ | 87 (46) |
| | 2 | 1735 (22)$^{*}$ | 288 (32) | 77 (17)$^{\#\#}$ | 211 (49) |
| Pre-hospital intubation, *n* (%) | 1 | 289 (9.4) | 124 (34) | 32 (18)$^{\#\#}$ | 92 (49) |
| | 2 | 511 (6.5)$^{**}$ | 244 (27)$^{*}$ | 55 (12)$^{\#\#}$ | 189 (44) |
| Via transferring hospital, *n* (%) | 1 | 797 (26) | 159 (44) | 99 (57)$^{\#\#}$ | 60 (32) |
| | 2 | 2299 (29)$^{**}$ | 452 (51)$^{*}$ | 292 (64)$^{\#\#}$ | 160 (37) |
| Transfer hospital ER GCS sum | 1 | 15 (7–15) | 7 (3–15) | 7 (3–14) | 5 (3–15) |
| | 2 | 15 (10–15) | 9 (3–15)$^{**}$ | 10 (3–15) | 9 (3–15) |
| Transfer hospital ER T-RTS sum | 1 | 12 (10–12) | 10 (8–12) | 10 (8–12) | 10 (8–12) |
| | 2 | 12 (10–12) | 11 (8–12)$^{**}$ | 11 (8–12) | 11 (8–12) |
| Intubated at transferring hospital, *n* (%)¶ | 1 | 165 (5.4) | 97 (27) | 57 (59)$^{\#\#}$ | 40 (67) |
| | 2 | 338 (4.3)$^{**}$ | 250 (28) | 141 (50)$^{\#\#}$ | 109 (76) |
| Physician-manned secondary transport (ground or air), *n* (%) | 1 | 229 (29) | 85 (54) | 44 (45)$^{\#\#}$ | 41 (69) |
| | 2 | 650 (29) | 240 (54) | 125 (43)$^{\#\#}$ | 115 (72) |
| Intubated in trauma centre ER, *n* (%)¶ | 1 | 368 (12) | 76 (21) | 35 (40)$^{\#\#}$ | 41 (67) |
| | 2 | 789 (10)$^{**}$ | 168 (19)$^{*}$ | 90 (35)$^{\#\#}$ | 78 (55) |
| Trauma centre ER GCS sum | 1 | 15 (8–15) | 6 (3–15) | 7 (3–15)$^{\#\#}$ | 4 (3–14) |
| | 2 | 15 (10–15)$^{**}$ | 7 (3–15)$^{**}$ | 8 (3–15)$^{\#\#}$ | 6 (3–15) |
| Trauma centre ER T-RTS sum | 1 | 12 (10–12) | 9 (6–12) | 10 (7–12)$^{\#\#}$ | 8 (4–12) |
| | 2 | 12 (10–12)$^{**}$ | 10 (7–12)$^{**}$ | 10 (8–12)$^{\#\#}$ | 9 (6–12) |
| ICU admission, *n* (%) | 1 | 2534 (82) | 338 (93) | 163 (94) | 175 (93) |
| | 2 | 6657 (85)$^{**}$ | 839 (94) | 428 (94) | 411 (95) |
| Ventilator treatment, *n* (%) | 1 | 690 (22) | 289 (80) | 123 (76)$^{\#\#}$ | 166 (95) |
| | 2 | 1422 (18)$^{**}$ | 668 (75)$^{*}$ | 306 (71)$^{\#\#}$ | 362 (88) |
| Ventilator days | 1 | 3 (1–15) | 4 (1–16) | 3 (1–13)$^{\#}$ | 5 (1–18) |
| | 2 | 3 (1–17) | 6 (1–25)$^{**}$ | 5 (1–19)$^{\#\#}$ | 9 (1–27) |
| Trauma centre days | 1 | 4 (1–13) | 5 (1–19) | 5 (2–16) | 6 (1–20) |
| | 2 | 3 (1–13)$^{**}$ | 8 (2–28)$^{**}$ | 6 (2–22)$^{\#\#}$ | 10 (2–34) |
| Discharged on a ventilator, *n* (% of total) (% of intubated pts.) | 1 | 299 (9.7) (43) | 196 (54) (67) | 65 (37)$^{\#\#}$ (52)$^{\#\#}$ | 131 (69) (78) |
| | 2 | 472 (6.0)$^{**}$ (33)$^{**}$ | 358 (40)$^{**}$ (53)$^{**}$ | 166 (36)$^{\#}$ (54) | 192 (44) (53) |
| Survival at 30 days, *n* (%) | 1 | 2936 (96) | 185 (51) | 96 (55) | 89 (47) |
| | 2 | 7607 (97)$^{**}$ | 628 (71)$^{**}$ | 320 (70) | 308 (71) |
| ISS | 1 | 10 (1–29) | 30 (25–50) | 26 (25–27)$^{\#\#}$ | 38 (30–57) |
| | 2 | 10 (1–26)$^{**}$ | 27 (25–50) | 26 (25–27)$^{\#\#}$ | 38 (30–54) |
| NISS | 1 | 13 (1–34) | 50 (26–66) | 43 (25–66)$^{\#\#}$ | 57 (43–75) |
| | 2 | 12 (1–34)$^{**}$ | 50 (30–66) | 50 (26–75)$^{\#\#}$ | 57 (43–75) |
| *W* statistic with 95% CI | 1 | 1.30 (0.73 to 1.88) | −9.44 (−13.23 to −5.64) | −17.54 (−22.80 to −12.27) | −1.98 (−7.43 to 3.47) |
| | 2 | 1.35 (1.00 to 1.70) | 3.33 (0.94 to 5.72) | −7.03 (−10.27 to −3.78) | 14.20 (10.68 to 17.72) |

Period 1 = 2001–2004, Period 2 = 2005–2011. Values are median (10–90 percentile) if not otherwise stated. ¶: Percent of available patients, i.e. those not arriving intubated. Chi Squared or Mann–Whitney *U* test: Statistically significant difference between Period 1 and Period 2: $^{*}p < 0.05$, $^{**}p < 0.01$. Statistically significant difference between isolated Head/Neck maxAIS 5 patients and multitraumatised Head/Neck maxAIS 5 patients within same Period: $^{\#}p < 0.05$, $^{\#\#}p < 0.01$.

Society of Anesthesiologists Physical Status Classification System (ASA-PS) [11,15].

*VLAD graph analysis*

From each consecutive patient's contribution, VLAD graphs were calculated with JMP 10 statistical software (www.jmp.com, SAS Institute Inc., Cary, NC, USA) using the CUSUM platform. Every patient was assigned a value corresponding to gained or lost fractional life, by subtracting that patient's calculated probability of survival (Ps) from the actual outcome, where 1 represented survival and 0 death. Thus, every survival contributed a reward of 1 − Ps and every death a penalty of −Ps. Starting from zero, each patient's contribution was added to the summed contribution of all previous patients, and the resulting number was plotted vs. patient number. The graph of the cumulative sum of penalties and rewards shows the difference over time between expected and actual cumulative survival. This represents the number of excess saved lives compared to the reference model since the first patient was admitted.

*Qualitative interpretation of VLAD graphs*

When the cumulative sum is plotted against consecutive patient number the graph will be unaffected by changes in number of admissions per time unit. Stable performance produces a linear VLAD graph. A linear horizontal VLAD graph denotes stable performance identical to that of the chosen reference model. A point of downward deflection indicates a decline in performance. An upward deflection of the graph suggests an improvement of performance at this time point. If the VLAD graph subsequently rises linearly, performance is stable but better than the reference model. Continuous, ongoing improvement in performance will create an upward-curving graph. We qualitatively evaluated VLAD graphs for different subpopulations with respect to changes in shape.

*Quantitative analysis*

Quantitative analysis of the VLAD graph shape was performed using piecewise linear regression in the JMP 10 Nonlinear platform. This method could formally identify a breakpoint in time, or rather the consecutive patient number after which there was an abrupt change in the VLAD graph slope. A formula was specified that represented an initial line with slope $b1$ and another line with slope $b2$ added to it from a breakpoint $C$, i.e. $Y = b0 + b1 \times X + b2 \times (X - C)$, with $X$ being patient number and $(X - C)$ set to zero for all $X$ values smaller than $C$. The two slopes and the breakpoint $C$ were calculated with 95% confidence intervals.

VLAD graphs were created for the entire population and for subpopulations stratified by (a) injury severity (ISS 1–15, ISS 16–24, ISS 25–75), (b) ISS body region (Head/Neck, Face, Chest, Abdomen/Pelvic contents, Extremities/Pelvic girdle, and External), and (c) maximum AIS score (maxAIS; 1–6) within each ISS body region.

The group of patients having at least one AIS score of 5 in the Head/Neck region was studied more in depth. Separate VLAD graphs were created for those with an isolated critical head or neck injury (ISS 25–27, i.e. allowing AIS score 1 injuries in up to two other body regions) and for multitraumatised patients with critical head or neck injury (ISS $\geq$ 28), since these two subgroups differ substantially with regard to epidemiological, injury and treatment factors.

*Subgroup analysis*

Patient subpopulations were compared (Table 1) by demographic descriptors, injury mechanism, physiological response to injury, provided pre- and in-hospital services and treatment, anatomic injury, 30-day survival, and $W$ statistic. Distribution of descriptive variables are given as medians with 10–90 percentiles if not otherwise stated. Groups were compared with the Wilcoxon Rank Sum test for continuous data and the Chi Squared test for categorical data. Time trends in continuous variables were explored with linear regression or non-parametric Cochran–Armitage test for trend as appropriate (JMP 10). A statistical significance level of 0.05 was used.

For patients having at least one AIS score of 5 in the ISS Head/Neck region, survival changes were studied for broad diagnostic groups, defined by combining AIS codes for anatomically similar cerebral injuries. Rare diagnoses were omitted. Diagnostic categories were (a) brain swelling/oedema not including peri-lesional oedema (AIS 14066*), (b) contusion (AIS 14060*, 14061*, 14062* excluding 140628), (c) intracerebral haematoma (AIS 140638, 14064*, 140678), (d) subarachnoid haemorrhage (AIS 140684), (e) subdural haematoma (AIS 14065*), (f) epidural haematoma (AIS 14063* excluding 140638), and (g) diffuse axonal injury (AIS 140628). These categories comprised AIS codes of different severities, and a patient with several anatomical injuries would be represented in several categories. Change in yearly survival rate within each diagnostic category was analysed with the Cochran–Armitage test for trend.

## Results

A total of 12,191 patients met the inclusion criteria; 12,180 had sufficient data to compute Ps and thus contribute to the VLAD graph. Median age was 35 years (14–70), 72% were males, 10.4% had pre-injury ASA-PS $\geq$ 3, and 91% suffered blunt injuries. Pre-hospital triage decided whether patients were transported to OUH–U, to lower level trauma hospitals, or to local emergency medical centres. Consequently, 41% of the study group had ISS $\geq$ 16. Median time from injury to arrival at OUH–U was 0.75 h (0.3–1.75 h) for patients arriving directly and 4 h (1.5–12 h) for transfer patients. Over the study period there was a steady increase in the number of admitted trauma patients per year (approx. 68 more patients/year; linear regression $p < 0.001$). The fraction of patients with ISS $\geq$ 16 decreased slightly by approximately 0.5% per year ($p < 0.01$, Cochran–Armitage test for trend). The total number of AIS codes was 27,951.

*VLAD graph analysis by ISS level*

The VLAD graph of the entire TR–OUH trauma population 2001–2011 is shown in Fig. 1A. During the first four years the institutional performance was quite similar to what would be expected from the underlying TRISS survival prediction model, with neither an accumulation of excess survivors nor deaths. From late 2004 the VLAD graph suddenly rises and continues almost linearly through 2011. The total number of excess survivors amounted to 141.

Fig. 1B shows that although survival also appeared to be increased in the other ISS groups, the major change in performance seemed to occur among the most severely injured patients (ISS 25–75). This group's VLAD graph can be described as consisting of two linear segments with different slopes. Using piecewise linear regression, a breakpoint was identified at consecutive patient number 3371 (95% CI 3325–3417), corresponding to being admitted Nov 28, 2004 (95% CI Nov 10–Dec 21). For practical reasons January 1, 2005 was chosen as the cutoff time for before-and-after performance analyses.

*VLAD graph analysis by ISS body region*

VLAD graphs were created for each of the six ISS body regions, further stratifying patients by their maximum AIS severity score (maxAIS) in that region (Fig. 2, Panel A–F). A patient with injuries to several ISS body regions would appear in VLAD graph panels for all those regions, but only in a single maxAIS group within a specific body region.

Most combinations of body region and injury severity (Fig. 2) had almost linear VLAD graphs, indicating unchanged overall performance. Two VLAD graphs however, were distinctly different from all others. The graph for External region, maxAIS 1 (Fig. 2F) showed an inflection point very similar to the graph for the total trauma population (Fig. 1A). As 8947 (73%) of the patients in our population were coded with at least one minor injury to the body surface, the External region maxAIS 1 graph probably reflected the shape of the VLAD graph for the total population, rather than being

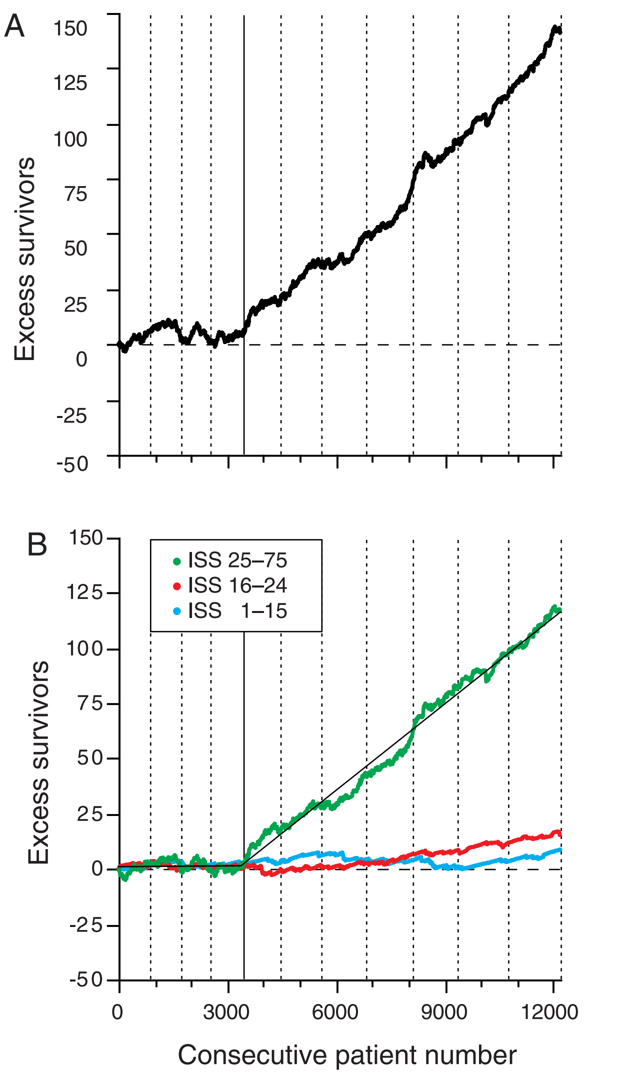


**Fig. 1.** VLAD graphs depicting cumulative sum of excess survivors as a function of consecutive patient number for the years 2001–2011. Dashed vertical lines separate calendar years; increased distance between lines are due to increased number of admitted patients per year. Linear VLAD graphs denote stable performance. Dashed horizontal lines represent performance according to the underlying TRISS survival prediction model, i.e. no excess survivors. Solid vertical line in all VLAD graphs represents January 1, 2005, separating Period 1 from Period 2. (A) Total population, 12,180 patients. (B) Total population stratified by Injury Severity Score (ISS), confirming the major performance improvement in the ISS 25–75 group. Solid lines superimposed on the ISS 25–75 group show the results of piecewise linear regression of the VLAD graph, highlighting both the increase in excess survivors and the time point at which the sudden change occurred.

caused by improved performance in the treatment of minor skin injuries.

The graph for ISS Head/Neck region patients with maxAIS 5 (1248 patients) had the most divergent shape (Fig. 2A). This graph was U-shaped, first pointing downward indicating lower performance than expected, then taking an almost horizontal course indicating performance similar to the reference model, and lastly climbing upwards indicating better performance than expected.

*VLAD graph analysis of subpopulations showing changes in survival*

Since multitraumatised patients would appear in VLAD graphs for several ISS body region panels in Fig. 2, fluctuations in some graphs might primarily reflect changes in performance for injuries in other regions. Therefore, mutually exclusive populations were defined and their VLAD graphs investigated.

The contribution to institutional performance in patients with maxAIS 5 in the Head/Neck region (shown in Fig. 2A) was compared with that of all other trauma patients (Fig. 3A). The latter group ($n$ = 10,932; 146 excess survivors) showed a linear, upward-sloping VLAD graph, indicating better performance than predicted by the TRISS model but unchanged throughout the entire study period ($R^2$ = 0.997). It thus appears that the change in treatment performance in late 2004, reflected in the VLAD graph for the total trauma population (Fig. 1A), was caused by the considerable changes in survival among patients with Head/Neck region maxAIS 5 ($n$ = 1248; −5 excess survivors).

In Fig. 3B separate VLAD graphs are displayed for (a) isolated maxAIS 5 Head/Neck injuries (ISS 25–27, $n$ = 627; −62 excess survivors) and (b) multitraumatised maxAIS 5 Head/Neck injuries (ISS ≥ 28, $n$ = 621; 58 excess survivors). Improved survival was demonstrated in both subgroups.

*Clinical description of subpopulations*

The subpopulations whose VLAD graphs are shown in Fig. 3 A and B differed substantially with respect to demographic factors, injury mechanism, physiologic response to injury, provided pre- and in-hospital treatment, injury severity, and 30-day survival (Table 1). Noticeable changes occurred from Period 1 (2001–2004), the years before the inflection point in the VLAD graph, to Period 2 (2005–2011) (Table 1). While the distribution of age and gender was unchanged, the proportion of patients with significant pre-injury medical conditions increased, and more injuries were caused by falls or violence. ISS and NISS decreased slightly in the population without critical head or neck injury, and GCS and T-RTS scores were generally higher.

Time from sustained injury to arrival at OUH–U was unchanged from Period 1 to Period 2 for patients arriving directly (median 44 min vs. 43 min; p = 0.92) but declined markedly for patients transferred from other hospitals. Transfer patients with isolated maxAIS 5 Head/Neck injury seemed to have the largest reduction in median time from injury to arrival at OUH–U (reduction 2 h 11 min; p < 0.001). The reduction for multitraumatised maxAIS 5 Head/Neck injury patients was 1 h 16 min (p < 0.02), for other head injured patients 1 h 5 min (p < 0.001), and for the remaining population 1 h 5 min (p < 0.01). This development paralleled an almost linear increase in helicopter-based physician-manned transports in our region during the study period (1067 missions in 2001, increasing by approximately 137 missions/year; $R^2$ = 0.86, p < 0.001).

At OUH–U, trauma team assessment of patients became swifter. From Period 1 to Period 2, time from admission to first CT scan was reduced from 39 to 29 min (p < 0.01 for all subgroups) and time to acute surgery was reduced from 1 h 45 min to 1 h 25 min (p < 0.02 for all subgroups). For patients without maxAIS 5 Head/Neck injuries, the fraction taken directly to surgery was unchanged (10.3% vs. 9.5%, p = 0.16). For maxAIS 5 Head/Neck patients, however, there was a marked increase in immediate neurosurgical procedures from year 2005, measured as a direct transfer from the ER or CT lab to the OR (Fig. 4). Their duration of ventilator treatment and length of trauma centre stay also increased substantially (Table 1).

Among patients with at least one maxAIS 5 injury in the Head/Neck ISS region, the mean number of Head/Neck AIS codes registered per patient increased slightly from 1.1 to 1.5 during the study period (p = 0.02; $R^2$ = 0.46). The yearly fraction of survivors increased in the diagnostic groups brain oedema, brain contusion, subarachnoid haemorrhage, subdural haematoma, and diffuse axonal injury (all p < 0.001; Cochran–Armitage test for trend). No significant changes in survival were seen for patients with epidural (p = 0.17) or intracerebral (p = 0.13) haematomas.

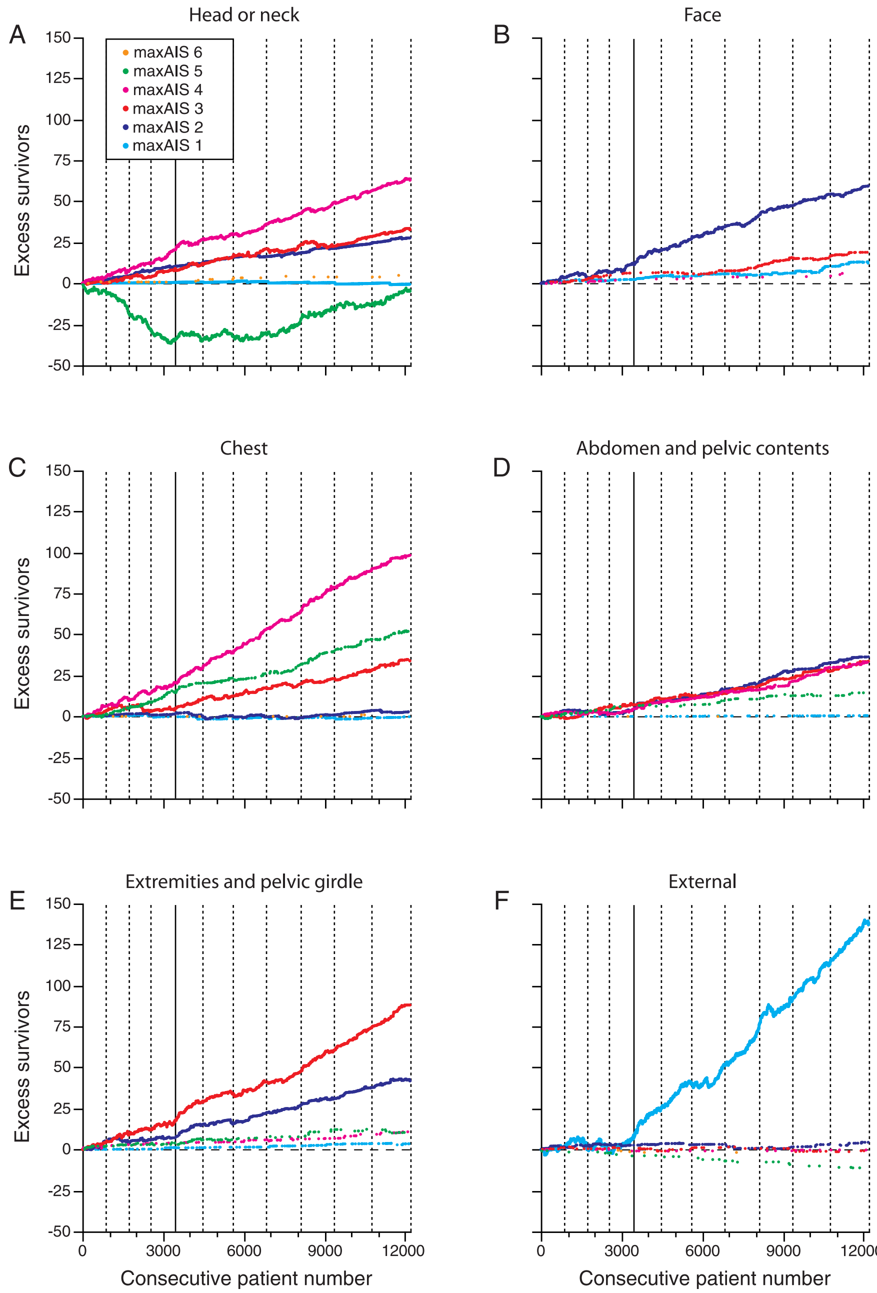


**Fig. 2.** VLAD graphs for all patients with one or more injuries in each specified ISS body region (A–F), stratified by maximum AIS (maxAIS) severity score in that region. A single patient may appear in several ISS body regions due to multiple trauma, but can only be assigned to one maxAIS graph within each ISS region. The graph for Head/Neck region patients with maxAIS 5 (1248 patients) had the most divergent shape (A). The External region maxAIS 1 graph (F) represents concomitant minor skin injuries in the total trauma population (cf. Fig. 1A).

*W* statistics increased from Period 1 to Period 2 both for the total group of patients with maxAIS 5 Head/Neck injury and for the two patient subgroups (isolated or multitraumatised injury) (Table 1). The remaining trauma population had identical *W* statistics in the two time periods, indicating stable, unchanged performance.

## Discussion

### *Main findings*

Using the VLAD technique on survival probability predicted by the TRISS model, we confirmed and extended our previous findings that 30-day survival for the entire TR–OUH trauma population started to increase from the end of 2004 and remained steadily improved throughout the study period [6,7]. The main improvement in survival was seen among the most severely injured patients (ISS $\geq$ 25), and patients with maxAIS 5 injuries in the ISS Head/Neck region seemed to represent the subpopulation in which the changes in survival took place. Compared to TRISS predicted survival, maxAIS 5 Head/Neck patients at OUH–U initially had poorer outcome, from 2005 had similar outcome, and from 2008 had better outcome than predicted. All other ISS injury region groups showed better survival than predicted by TRISS, but to an unchanged degree throughout the study period.

### *Limitations of the study*

This was an exploratory, retrospective study, and our findings must therefore be viewed as hypothesis generating. We used the

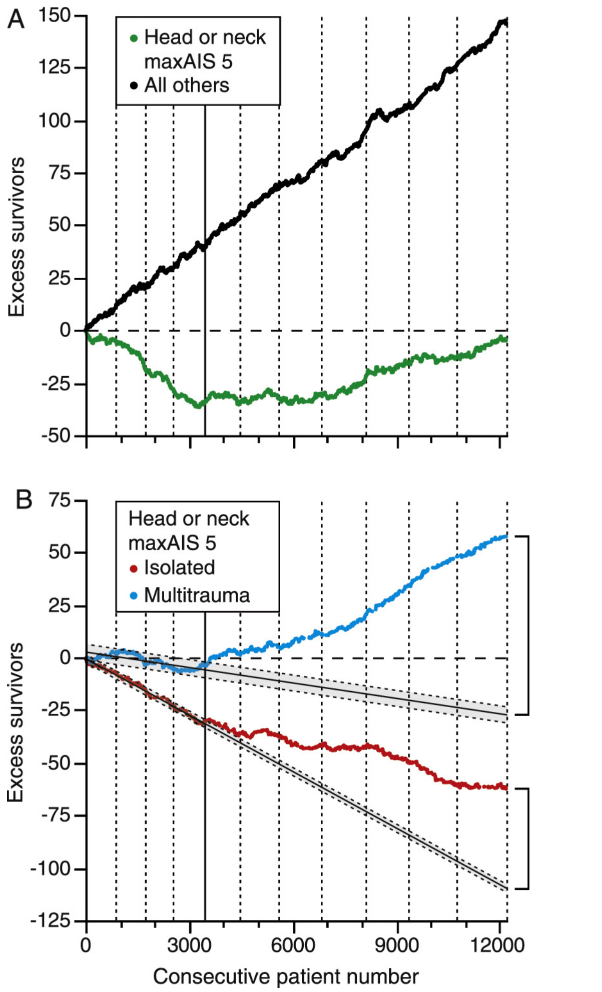


**Fig. 3.** VLAD graphs for mutually exclusive subpopulations. (A) Patients with maxAIS 5 in the Head/Neck ISS body region versus the remaining study population. Note the U-shaped graph for patients with critical head or neck injuries indicating large performance changes, in contrast to the linear VLAD graph indicating unchanged overall performance for the remaining group. (B) Patients with Head/Neck maxAIS 5, split into two subgroups: Isolated injury patients (ISS 25–27) versus multitraumatised patients (ISS $\geq$ 28). Regression lines with 95% prediction intervals for each subpopulation in Period 1 are extrapolated through Period 2. Brackets denote increase in excess survivors from the extrapolated regression lines.

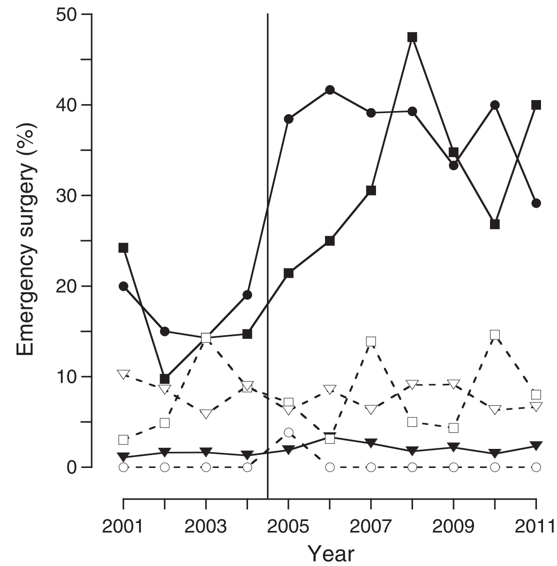


**Fig. 4.** Increase in fraction of trauma patients arriving directly to OUH–U who underwent emergency surgery, defined as being taken directly from the ER or CT lab to the OR. Circles: Patients with isolated maxAIS 5 Head/Neck injury. Squares: Multitraumatised patients with maxAIS 5 Head/Neck injury. Triangles: Remaining trauma population. Continuous lines/Filled symbols: Neurosurgery. Dotted lines/Open symbols: Orthopaedic or general surgery. A large increase in emergency neurosurgical procedures in patients with critical neurotrauma occurred in 2005. No changes occurred in other subgroups.

VLAD technique on Ps values calculated from the TRISS survival prediction model, stratifying our trauma population by injured ISS body region and further by maximum degree of injury in that region (AIS 1–6). The TRISS model is derived from a large, general trauma population and is not validated for subpopulations. Consequently, findings in stratified analyses should only be compared within strata from the same institution over time.

A limitation of our material is that we only have 30-day survival as outcome measure. The proportion of trauma deaths occurring later than this time point may vary between patient groups [16]. It would be of great interest to repeat our analyses on 6- and 12-month survival data and to see the method used on datasets from other trauma registries. Moreover, there is a strong need to investigate and monitor non-fatal outcomes after trauma [17,18].

The TRISS model coefficients are regularly updated, but the set of explanatory variables in the model and their mathematical representations (e.g. categorical rather than continuous, choice of cutoff points) remain fixed. This may introduce bias if the model is used in patient populations that differ markedly from the TRISS derivation population. Institutions may therefore show different survival rates than predicted from TRISS due to their quality of care, but also due to differences in case mix if these are not well controlled for by the model. Our stratified analyses therefore only focused on whether there were *changes* in slope of the VLAD graphs. Moreover, implications of possible changes in case mix during the study period were main focus points in our analysis.

The subpopulation displaying improved survival in our study was defined by having at least one critical head or neck injury, AIS severity score 5. Still, compared to Period 1, in Period 2 these patients had higher GCS scores and T-RTS values and were less often artificially ventilated both prehospitally and at the trauma centre. Thus, we cannot rule out the possibility that a shift in admitted injuries did occur, and that the AIS system does not fully reflect injury severity. All patients were coded according to the same AIS catalogue and by the same certified coders, and though there seemed to be slow shifts in the relative frequency of head and neck diagnoses used (data not shown), survival among maxAIS 5 Head/Neck patients improved in a similar manner across broad diagnostic groups. Moreover, the GCS and RTS scores are constituents of the TRISS model and adjusted for when Ps is calculated.

*Why improved survival in one trauma subpopulation?*

The sudden improvement in survival in our trauma population appeared to result predominantly from improved survival in patients with very severe head or neck injury, both as isolated injuries and in multitraumatised patients. These findings could result from specific changes in the treatment of patients with critical neurotrauma. Additionally, patients with critical neurotrauma could constitute a particularly vulnerable group, an “indicator population” that to the highest degree benefitted from general improvements in the trauma treatment chain, from the site of injury, during transport, in the ER, OR, ICU and hospital ward.

*Referral pattern and referral times*

The fraction of admitted trauma patients that had at least one head or neck AIS 5 injury was unchanged through the study period.

However, an overall higher proportion of patients was transferred from lower-level hospitals, and among transfer patients, time from sustained injury to arrival at OUH–U declined most markedly for those with isolated critical neurotrauma. This pattern of more frequent and swifter transfers may have resulted from changes in trauma care at local hospitals, in transfer services, and at OUH–U.

Lower-level hospitals probably benefitted from the increased formalisation of trauma care taking place at OUH–U, regionally, and nationally. Improved awareness of and competence towards trauma patients would be expected as the crew resource management course BEST (Better & Systematic Trauma Care, www.bestnet.no) was introduced at lower-level hospitals in our region from year 2000 through 2005. ATLS (Advanced Trauma Life Support) courses were introduced in 2004 and DSTC (Definitive Surgical Trauma Care) courses in 2006. Concurrently, regular regional trauma meetings were organised, aiming at closer collaboration between OUH–U, the pre-hospital services, and referring hospitals.

In 2006, OUH–U formalised that all contact concerning possible referral of trauma patients from local hospitals should be with the trauma team leader, not the perceived "organ surgeon" (e.g. neurosurgeon or orthopaedic surgeon). This probably increased uniformity of assessment of relevant patient factors and ensured that also transfer patients were received by the OUH–U trauma team upon arrival.

Informal and gradual referral and admittance policy changes could have occurred with increased awareness of the potential in interventional radiology, surgery, and intensive care. Such effects might have been most pronounced for elderly patients with significant comorbidity. Among admitted patients with isolated critical head or neck injury in Period 2, age was unchanged but the proportion with comorbidities was increased. Interestingly, this should have been expected to decrease survival. The TRISS model does not adjust for comorbidities, thus the observed upward change in the VLAD graphs might be an underestimation of true improved performance. ASA-PS has previously been shown to be an independent negative predictor of survival after trauma [15,19].

*Pre- and inter-hospital transfer services*

The availability of specialised physician-manned pre- and inter-hospital transfer in our region increased markedly from 2005 when the number of helicopters in service was increased. The improved capacity could have contributed to the marked decline in time from injury to arrival at OUH–U among transfer patients. Reduced delay to neurosurgical assessment, with maintained high level of care during transport, could have contributed to improved survival in vulnerable patients. Even so, approximately 30% of multi-traumatised and 55% of isolated maxAIS 5 Head/Neck injured patients were transferred from lower-level hospitals to OUH–U attended by paramedics.

*Trauma team factors*

Internal audits and formal research on trauma team activation and surgical competence [20,21] led to stepwise upgrading of the OUH–U trauma system from around year 2000. Requirements for surgical education and experience for trauma team leaders were refined in 2002 [7], a dedicated trauma service was formalised in 2005, and criteria for trauma team use were revised. ATLS and DSTC courses were required for both the trauma team leader and the consultant anaesthesiologist in the trauma team. A trauma course for nurse anaesthetists, ER nurses, OR nurses and radiographers was introduced.

A marked change in practice for fluid resuscitation and blood product use started around 2004 with increasing awareness of the importance of preventing traumatic coagulopathy. Procedures were implemented for better patient temperature control, less use of crystalloids, balanced transfusion with red blood cells, plasma and platelets in massive bleeding, damage control resuscitation targeted to normalise lactate and Base Excess, damage control surgery, and angio-embolisation. Hypertonic saline was introduced as a resuscitation fluid in head trauma patients and as rescue against high intracranial pressure. The practice changes may especially have benefitted patients with critical neurotrauma, who are exceedingly vulnerable to poor oxygen transport as well as oedema. Effects on survival would be harder to detect in our remaining trauma population, where mortality was only 3.6% and deaths directly due to exsanguination were infrequent given our setting with 91% blunt trauma.

*Neurosurgical presence and competence*

Planning of improvements of neurotraumatological services at OUH–U was initiated in 2001 with a new head of the Department of Neurosurgery. The overall result was an increased neurosurgical involvement in trauma patients. Active recruitment of skilled neurosurgeons started in 2003. From 2005, rotas were changed from a two-level to a three-level schedule, adding an experienced specialty registrar or young consultant available at all times to the in-hospital junior doctor and the on-call consultant neurosurgeon. This ensured much more competent neurosurgical assessment in the ER and continuity of competence in the ICU during the night. A more ambitious treatment practice seems to have followed. Fig. 4 shows that among directly arriving (i.e. unselected) patients with AIS 5 neurotrauma, the fraction who underwent emergency neurosurgical interventions including invasive monitoring almost doubled from 2004 to 2005.

Upgraded neuroradiological services supported swifter and better diagnostics, and neuroradiological technology developed. Interventional neuroradiology was restarted in 2002 and developed to a fully equipped interventional unit. MRI service improved year by year, achieving 24/7 accessibility and competence late in Period 2.

*Neurointensive care systems*

From 2004 two senior neurosurgeons and from 2005 two senior intensivists were specifically dedicated to neurointensive care, increasing consistency and continuity of treatment. Measures of early rehabilitation of neurotrauma patients started in 2002 and were formalised for traumatic brain injury patients in 2005. In 2009 a multidisciplinary group of physicians decided upon a protocol on intensive care for serious traumatic brain injury.

The treatment of subarachnoid haemorrhage (SAH) also developed through the years. Comprehensive guidelines for treatment from OUH–U admission until discharge were released in 2006. These guidelines listed in detail levels of physiological measurements that should trigger respiratory, circulatory, or surgical interventions, with their pathophysiological rationale. It is reasonable to assume that implementation of procedures assigned to optimise brain oxygenation and perfusion in SAH patients throughout the neurocritical treatment chain may have had positive spillover effects also on neurotrauma patients, who were treated by the same personnel in the same hospital areas.

Ventilator treatment was less frequent in all patient subgroups in Period 2, but those who did receive ventilator treatment in Period 2 had more ventilator days. Increased use of non-invasive ventilatory support as an alternative to sedation and intubation is a possible explanation; unfortunately we do not have data on this. In contrast to other trauma patients, those with maxAIS 5 Head/Neck injuries had longer trauma centre stays in Period 2, possibly reflecting an overall improved focus on neurointensive care.

## Conclusions

In a survey of all OUH–U trauma registry patients in an eleven-year period, we used the Variable Life-Adjusted Display (VLAD) technique on Ps values calculated from the TRISS model, and confirmed a sudden improvement in 30-day survival around the end of 2004 [6,7]. Stratifying our material, we found that patients with critical neurotrauma (maxAIS 5 Head/Neck injury) represented the patient group where survival improved most. Our remaining trauma population showed stable survival, superior to TRISS predicted.

We discuss a number of system changes targeted to improve general and neurotrauma care that may underlie our findings. Increased neurosurgical presence, competence, dedication and continuity from the ER through the ICU seems to be crucial. Similarly important is a well-run general trauma system of surgeons, anaesthesiologists, intensivists, radiologists, nurses and paramedics.

Our study demonstrates a method for continuous system analysis that can detect small changes in patient outcome with a high time resolution, changes that may result from system interventions or incidental events. Availability of long-term survival data would increase the usefulness of VLAD further. We encourage other trauma centres to retrospectively explore their data with stratified VLAD analyses and to prospectively monitor future system changes.

## Authors' contributions

NOS and TE designed and built the Oslo University Hospital Trauma Registry. RH monitored and documented changes in the trauma service in general and neurotrauma specifically. SS and TE planned and designed the study, carried out the statistical analyses, drafted the manuscript and created the figures. All authors critically evaluated and discussed the ongoing analyses, critically revised the manuscript, and approved the final version.

## Conflicts of interest

The authors declare that they have no conflicts of interest.

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